

Microlens Terrestrial Parallax Mass Measurements: A Rare Probe of Isolated Brown Dwarfs and Free-Floating Planets

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ABSTRACT

Terrestrial microlens parallax is one of the very few methods that can measure the mass and number density of isolated dark low-mass objects, such as old free-floating planets and brown dwarfs. Terrestrial microlens parallax can be measured whenever a microlensing event differs substantially as observed from two or more well-separated sites. If the lens also transits the source during the event, then its mass can be measured. We derive an analytic expression for the expected rate of such events and then use this to derive two important conclusions. First the rate is directly proportional to the number density of a given population, greatly favoring low-mass populations relative to their contribution to the general microlensing rate, which further scales as $M^{1/2}$ where M is the lens mass. Second, the rate rises sharply as one probes smaller source stars, despite the fact that the probability of transit falls directly with source size. We propose modifications to current observing strategies that could yield a factor 100 increase in sensitivity to these rare events.

Subject headings: gravitational lensing: micro — planetary systems

1. Introduction

It is extremely difficult to detect and measure the mass of dark isolated objects and systems. The only known method is to detect the object in a gravitational microlensing event and then to measure two non-standard parameters: the angular Einstein radius (on the plane of the sky) θ_E and the projected Einstein radius (on the observer plane) \tilde{r}_E . The lens mass and distance are then given by (Gould 1992)

$$M = \frac{\theta_E}{\kappa \pi_E}, \quad D_L = \frac{\text{AU}}{\pi_{\text{rel}} + \pi_S} \quad \kappa \equiv \frac{4G}{c^2 \text{AU}} \sim 8.1 \frac{\text{mas}}{M_\odot} \quad (1)$$

where $\pi_{\text{rel}} \equiv (\text{AU}/D_L - \text{AU}/D_S)$ is the lens-source relative parallax, π_S is the source parallax, and

$$\pi_{\text{rel}} = \theta_E \pi_E, \quad \pi_E \equiv \frac{\text{AU}}{\tilde{r}_E}. \quad (2)$$

These require measurement of two independent higher-order effects (microlens-parallax effects and finite-source effects) each of which is only rarely measured individually. Hence, mass measurements of dark lenses are quite rare.

An important exception to this rule is binary lensing, of which planetary lensing may be considered a special case. Binary lenses have extended caustics, and when the microlensed source passes close to or over one of these caustics (which it does in the majority of recognized binary-lens events), then finite-source effects become important, so that one can easily determine $\rho = \theta_*/\theta_E$, the ratio of the angular size of the source to the angular Einstein radius. Using standard techniques (Yoo et al. 2004), one can then infer θ_* from the source position on the color-magnitude diagram and so obtain θ_E . It is still relatively rare that the second higher-order parameter π_E can be measured, but at least a concatenation of two rarities is not required. Hence there are of order a dozen such measurements.

However, for isolated lenses, the caustic structure is simply a point at the position of the lens. Unless the limb of the source passes directly over this point, ρ cannot be measured photometrically.¹ The probability of such a chance alignment is simply ρ , and since $\rho = \theta_*/\theta_E \sim \mathcal{O}(\mu\text{as})/\mathcal{O}(\text{mas}) \sim 10^{-3}$, such events occur only a few times among the several thousand events discovered each year. Nevertheless, as Gould (1997) pointed out, it is just these extreme microlensing events (EMEs), with peak magnifications $A_{\text{max}} \sim \rho^{-1} \sim 10^3$ that could be susceptible to a “terrestrial parallax” measurement of π_E .

In principle, the “microlens parallax” π_E can be measured whenever observations are carried out from two or more locations within the Einstein ring projected onto the observer plane. This is because the event appears different from the two locations, and the amount of difference scales as \tilde{r}_E^{-1} (or linearly with π_E). In practice, however, events normally appear identical at different locations on Earth because typically $\tilde{r}_E \sim 1\text{--}10$ AU, i.e., $\sim 10^{4.5}$ times larger than the distance between observatories. For this reason, Refsdal (1966) originally proposed that microlens parallaxes be measured from a satellite in solar orbit. Gould (1992) proposed an alternate method: making use of the Earth’s orbital motion to measure π_E , but this requires events that remain substantially magnified for a large fraction of a year, and these are rare. Moreover, very long events most often have large Einstein radii, which reduces further the probability of the lens passing over the source limb.

¹It can in principle be measured astrometrically (Høg et al. 1995; Miyamoto & Yoshii 1995; Walker 1995), but this requires a level of astrometric precision that has not yet been achieved.

Hardy & Walker (1995) showed that given the steep magnification profiles characteristic of binary-lens caustics, it would be possible to distinguish the lightcurves even from two observatories on Earth. Then Holz & Wald (1996) pointed out that given enough photons, one could in principle distinguish the lightcurves of the much smoother point-lens events. Gould (1997) effectively combined these two ideas by noting that during EMEs, the source passes very close to the point-lens caustic (the very feature that permits a measurement of θ_E), thus also permitting a terrestrial parallax measurement of π_E , and so $M = \theta_E/\kappa\pi_E$.

Here we derive an analytic formula for the rate of terrestrial parallax mass measurements and use this to draw several important conclusions. We show that the actual number (2) of published terrestrial parallax mass measurements is higher than predicted by this formula and examine possible reasons for this. Finally, we propose methods to greatly increase the rate of terrestrial parallax mass measurements in the future.

2. Rate of Terrestrial Parallax Measurements

To measure the mass using terrestrial parallax, four conditions are required. First, the source size projected onto the observer plane must be $\rho\tilde{r}_E \lesssim 50 R_\oplus$. Otherwise the difference in magnifications $\mathcal{O}((\rho\tilde{r}_E)^{-1})$ will be less than a few percent, making robust measurement difficult. Since $\rho = \theta_*/\theta_E$ and $\pi_{\text{rel}} = \theta_E\pi_E$, this implies

$$\pi_{\text{rel}} = \theta_E\pi_E = \frac{\text{AU}}{\rho\tilde{r}_E}\theta_* \gtrsim 0.28 \text{ mas} \frac{\theta_*}{0.6 \mu\text{as}} \quad (3)$$

Hence, for typical microlensed sources, $\theta_* \gtrsim 0.6 \mu\text{as}$, the lens should be closer than $D_{\text{max}} = 2.5 \text{ kpc}$.

Second, the mass measurement requires that the lens transit the source. The rate of such events per star that also satisfy the first condition is

$$\Gamma = 2\langle\mu\rangle\theta_* \int_0^{D_{\text{max}}} dD_L D_L^2 n(D_L) = 1.6 \text{ Gyr}^{-1} \left(\frac{\langle\mu\rangle}{10 \text{ mas/yr}} \right) \left(\frac{\theta_*}{0.6 \mu\text{as}} \right) \left(\frac{D_{\text{max}}}{2.5 \text{ kpc}} \right)^3 \left(\frac{\langle n \rangle}{1 \text{ pc}^{-3}} \right) \quad (4)$$

where $n(D_L)$ is the local number density of lenses, $\langle n \rangle$ is its mean over the volume, and $\langle\mu\rangle$ is the mean lens-source relative proper motion. Note in particular that the rate depends only on the number density of lenses, not on their mass. This favors brown dwarfs and free-floating planets over stars because they are more common (Sumi et al. 2011).

Third, the peak of the event must be simultaneously observable from two sites that are separated by a substantial fraction of R_\oplus . This imposes three constraints. First, if the observatories are too close, then they will lack sufficient baseline for a measurement.

Second, if they are too far apart (such as Chile and New Zealand) then their observing windows will rarely overlap. Third, the event must occur within the 3-4 months of the peak of the observing season or simultaneous observation from well-separated observatories is not possible. An exception would be pairing northern observatories (each of which has an extremely short observing window) with southern observatories. It should be noted both published terrestrial-parallax mass measurements (described below) have in fact combined northern and southern observations.

Finally, obviously, the event must actually be observed. Aggressive observation of high-magnification events has been ongoing since 2004, with roughly half of all cataloged high-mag $A_{\text{max}} > 200$ events effectively covered (Gould et al. 2010). If we assume that $n \sim 1 \text{ pc}^{-1}$ stars, brown dwarfs, and free-floating planets locally (Sumi et al. 2011), that the target season is 1/4 of the year, that about 1/10 of events peak when they can be simultaneous observed from widely separated sites, and that the surveys effectively monitor $N \sim 5 \times 10^8$ sources (including those blended with other stars), we would have expected $(1/4)(1/10)(1/2)\Gamma NT = 0.1$ terrestrial parallax mass measurements, where $T = 10 \text{ yr}$ is the duration of the search to date. Hence, the probability of having two such measurements is about 5×10^{-3} , which is small enough that a closer examination of the detections is warranted.

3. Comparison to Observations

To date, there have been two published terrestrial parallax mass measurements, OGLE-2007-BLG-224 (Gould et al. 2009) and OGLE-2008-BLG-279 (Yee et al. 2009). The key features of these events are compared in Table 1.

The only thing that is “typical” about these events relative to the fiducial numbers in Equation (4) is that the source sizes are typical for observed microlensing events, $\theta_* \sim 0.6 \mu\text{as}$. Regarding peculiar features, let us first examine OGLE-2008-BLG-279. Terrestrial parallax was measured despite the fact that $\rho\tilde{r}_{\text{E}} = 100 R_{\oplus}$, twice the value suggested above. As a direct consequence of this fact and Equation (3), terrestrial parallax was detected at

Table 1: EVENTS WITH TERRESTRIAL PARALLAX

Name	M (M_{\odot})	D_L (kpc)	μ (mas/yr)	θ_* (μas)	$\rho\tilde{r}_{\text{E}}$ (R_{\oplus})	t_{E} (day)	A_{max}
OGLE-2007-BLG-224	0.056	0.5	48.0	0.77	10	106	2400
OGLE-2008-BLG-279	0.64	4.0	2.7	0.54	100	7	1600

$\pi_{\text{rel}} \sim 0.13 \text{ mas yr}^{-1}$, i.e., at a distance 1.6 times larger than estimated in Equation (4), which encloses a 4-times larger volume. Although not immediately obvious, this detection was made possible by the relatively slow proper motion and relatively high lens mass. Together, these resulted in an exceptionally long Einstein timescale $t_E = 106$ days. Hence, despite the extremely high magnification, the effective timescale $t_{\text{eff}} = 1.6$ hr was long enough to enable very dense observations over the peak from multiple observatories, which in turn permitted more precise measurement of subtle effects. See Figure 1 of Yee et al. (2009).

OGLE-2007-BLG-224 by contrast was detected at only $D_L = 0.5 \text{ kpc}$, i.e., within a volume that is 125 times smaller than envisaged by Equation (4). This proximity is partially responsible for the high proper motion, which somewhat compensates for the reduced volume. However, the primary reason for the high proper motion is that the lens is in the thick disk, whose number density is much lower than the thin-disk normalization of Equation (4). Due to the low mass and high proper motion, OGLE-2007-BLG-224 had a very short $t_E = 7$ days, so that given the high magnification, the effective timescale was only $t_{\text{eff}} \sim 4$ min, by far the shortest ever recorded. This made it extremely difficult to organize and take observations over the peak, but the exceptionally small $\rho \tilde{r}_E = 10 R_{\oplus}$ meant that a robust terrestrial parallax measurement was still very feasible.

In brief, neither of these two events “fits the mold” sketched by Equation (4). Whether these discrepant features are connected with the higher-than-expected event rate cannot be assessed without more events of this type.

4. Increasing the Rate of Terrestrial Parallax Mass Measurements

Because terrestrial-parallax mass measurements are a unique probe of low-mass isolated objects, it is worth some thought as to how to increase their rate. We present three ideas that, together, could improve the effective sensitivity by two orders of magnitude. First, by aggressive monitoring of ongoing microlensing surveys, it should be possible to recognize many more faint-source high-magnification events in real time. At present, only the MOA collaboration even attempts to recognize “new events” arising from uncatalogued sources in real time, and MOA observing conditions are far less ideal than those in Chile or Africa where other existing and planned surveys are located. Such faint-star sources are extremely important because the total rate per star scales as

$$\Gamma \propto \theta_* D_{\text{max}}^3 \sim \theta_*^{-2} \left[1 + \frac{0.4}{\theta_*/0.6 \mu\text{as}} \right]^{-3}, \quad (5)$$

where we have used $D_L = \text{AU}[\theta_*(\text{AU}/\rho \tilde{r}_E) + \pi_S]^{-1}$ and assumed $\rho \tilde{r}_E < 50 R_{\oplus}$ and $\pi_S = 125 \mu\text{as}$. Hence, physically smaller sources each have a much higher rate, and there are more

small stars than big stars. Because terrestrial-parallax mass measurements already *require* high-magnification, these intrinsically faint sources will still yield high signal-to-noise ratio measurements. Now, in principle, even if these are not announced in real time, they may still be simultaneously monitored from two continents by routine survey observations. However, as discussed in Section 2, this is relatively unlikely.

A second suggestion, then, is the addition of many northern telescopes to the network of followup observatories. As mentioned above, each such observatory would have a very narrow window and so a very limited number of high-magnification events that it could monitor. This would be an advantage in the sense that it would require a limited commitment. By the same token, a large number of such observatories would be needed to effectively cover the 24-hour day. But with such coverage, the number of monitored events could be increased by a factor 10 by creating a $\sim 1 R_{\oplus}$ north-south baseline for almost all events in place of the current $\sim 1 R_{\oplus}$ east-west baseline that exists for a small fraction of events.

Finally, at present there are a very large number of microlensing events discovered by survey teams in low-cadence fields whose nature as high-magnification cannot be effectively predicted based on these sparse data. These events could be monitored by a network of “robotically intelligent” narrow angle telescopes, with feedback loops aimed at acquiring enough data to adequately predict high magnification. The same feedback loops could then enable these telescopes to undertake the several-site intensive monitoring needed for terrestrial parallax measurements. RoboNet (Tsapras et al. 2009) is an example of such a network, which is presently under construction and is in partial operation. It uses web-PLOP (Snodgrass et al. 2008) to compile an optimal list of targets and SIGNALMEN (Dominik et al. 2007) and ARTEMiS (Dominik et al. 2008) to evaluate possible lightcurve anomalies and redirect observations. While prediction and multi-site observations of terrestrial parallax events is not presently a goal of this network, it could be adapted to this purpose without major modifications.

5. Conclusions

Terrestrial parallax is one of the very few methods of measuring the mass and distance of isolated, dark, low-mass objects. We have shown that the rate of such events is directly proportional the *number* of target objects, which greatly favors brown dwarfs and planets since these probably account for a majority of the number of all lenses, but a small fraction of the event rate.

To date, only two terrestrial parallax mass measurements have been made, but this

already greatly exceeds the the number expected based on the estimate given by Equation (4). The reason for the discrepancy is not understood. It may be connected with the “unusual” character of these two events, which we detailed in Section 3, or it may be a $\sim 5 \times 10^{-3}$ statistical fluctuation.

The rate of terrestrial parallax mass measurements could be increased by a factor 10 simply by monitoring the relatively rare candidate events from many more sites, particularly in the northern hemisphere. A further increase of several-to-ten could be achieved by aggressively identifying intrinsically faint sources for possible high magnification, since smaller sources are much more likely to yield terrestrial parallax mass measurements according to Equation (5). Finally, a large fraction of high-magnification events are currently going unharvested in low-cadence survey fields, which could be rectified by a network of robotic telescopes such as RoboNet.

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